Studies of Flat Bunches in the Tevatron

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Fermilab

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Outline

- Background
- Recent Beam Studies on Flat bunches
- **Proposal:**
  - **Study Flat bunch beam in the Tevatron**
  - **Theoretical Studies of Flat Bunches**
- Summary

Bunches with Uniform Line-charge Distribution

Motivation

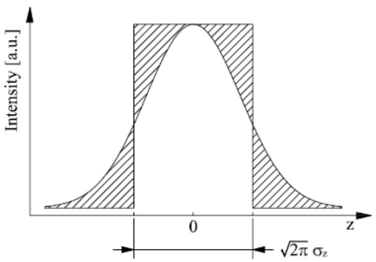
- There is on an going program at the LHC to upgrade the luminosity from its design value **1x10^{34} cm^{-2}sec^{-1}** to **1x10^{35} cm^{-2}sec^{-1}**.This poses daunting challenges. It is, therefore, necessary to explore seriously all of the viable options.
- The Large Piwinski angle or **"Flat Bunch scheme"** has the potential to yield 40% higher luminosity than Gaussian bunches for the same bunch intensity and the total beam-beam tune shift if the flat-bunch line intensity is kept the same as level as the Gaussian peak intensity.

(F. Ruggiero and F. Zimmermann (PRST-AB-Vol. 5, 061001 (2002))

The Piwinski angle ϕ, is given by,

$$\phi = \frac{\theta_c \sigma_z}{2\sigma_x}$$

θ_c is crossing angle
σ_z is RMS bunch length
σ_x is RMS transverse size



Therefore by flattening the bunch and with an increase in bunch intensity one can reach the ultimate luminosity at LHC.

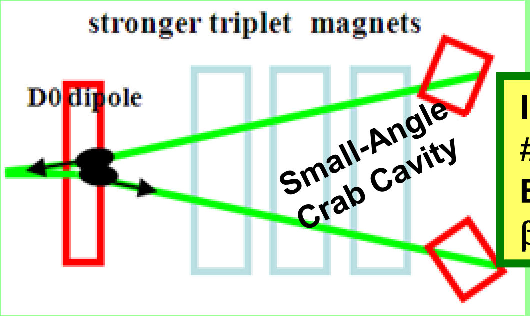
Hence the interest in flat bunches !

LHC upgrade paths with L≥ 10^{35} $cm^{-2}sec^{-1}$

(F. Zimmermann, CARE-HHH Workshop, 2008)

Full Crab Crossing (FCC)

L. Evans,
W. Scandale,
F. Zimmermann

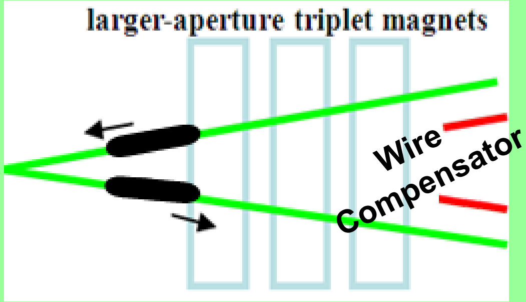


I=1.7E11ppb
\# of Bunch=2808
Bunch Spacing=25ns
β*~10 cm

- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat **ε⊥=3.75μm**

Large Piwinski Angle (LPA)

F. Ruggiero, W. Scandale.
F. Zimmermann



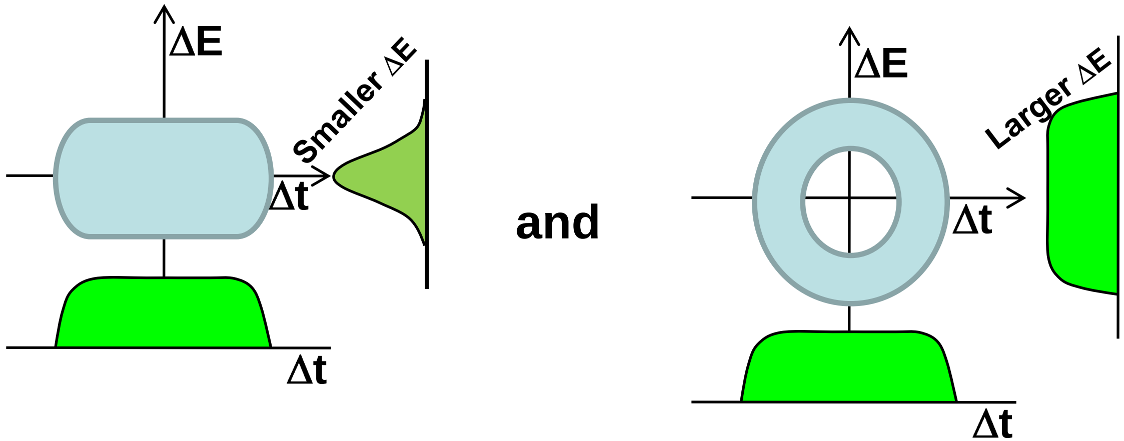
I~6E11ppb
\# of Bunch=1404
Bunch Spacing=50ns
β*~25 cm

~4 time more beam/bunch!

- long-range beam-beam wire compensation
  → **novel operating regime for hadron colliders**, beam generation
  ε⊥=3.75 μm

“Flat Bunches”
Types and Generation

- Flat Bunches come in two forms



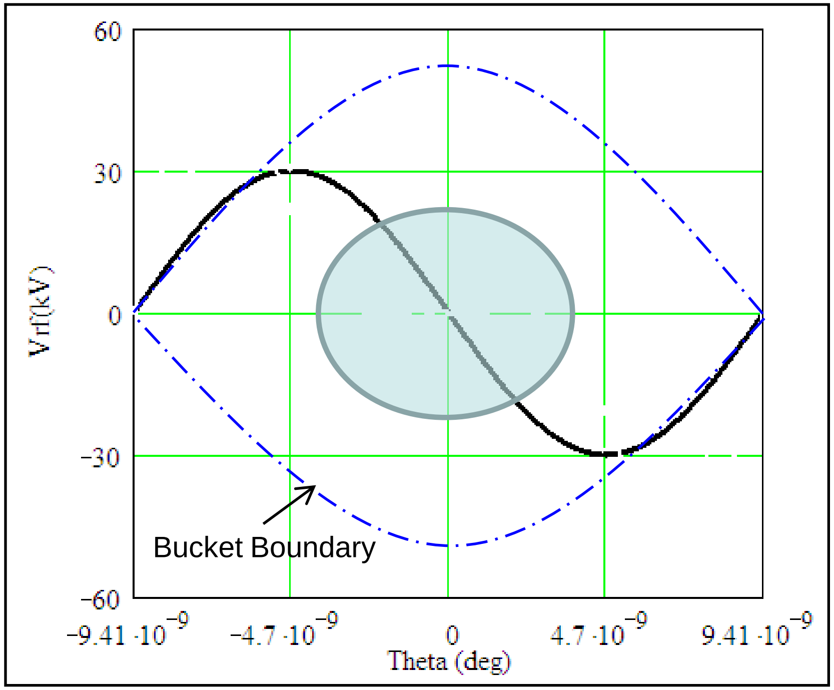
- There are two distinct methods to create flat bunches
  - ❑ Barrier rf ← Like that in the Recycler
  - ❑ Resonant rf systems
    - ➢ Double, triple or multiple harmonic rf system → Ideal one
    - ➢ Longitudinal hollow bunches, Carli’s technique

Historically a lot of work has been done at CERN on beam in double harmonic systems. Currently, more studies are being carried out in the SPS by Elena Shaposhnikova & collaborators

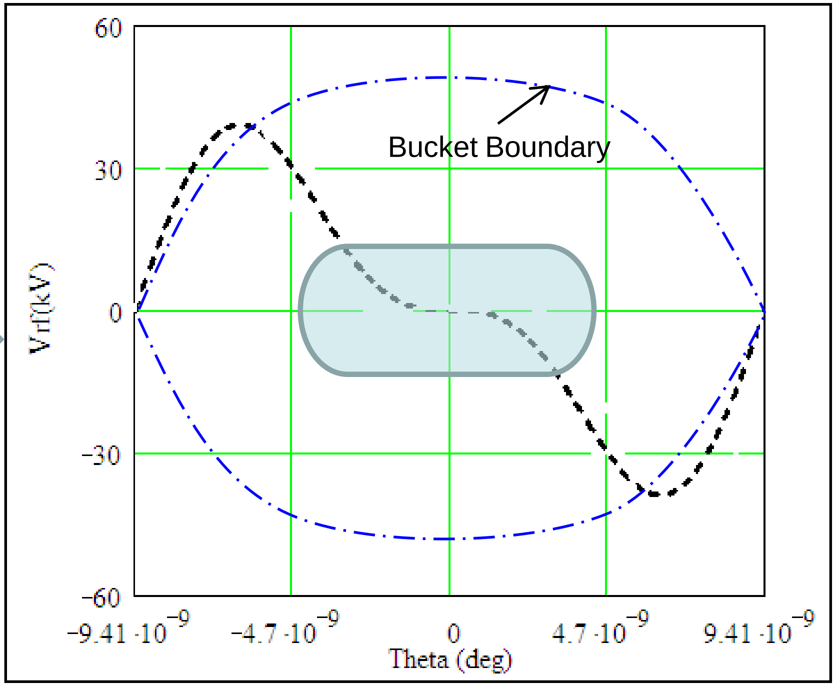
It is very important to study the single and multi-bunch stability issues of beam in **Double** & **Triple** harmonic rf buckets.

Flat Bunch with Double Harmonic RF waves
(A simple schematic view of the concept)

Beam in
Single Harmonic RF wave



Beam in
Double Harmonic RF wave



PS Studies at 26 GeV:
Stable Flat Bunches using Double-harmonic rf System

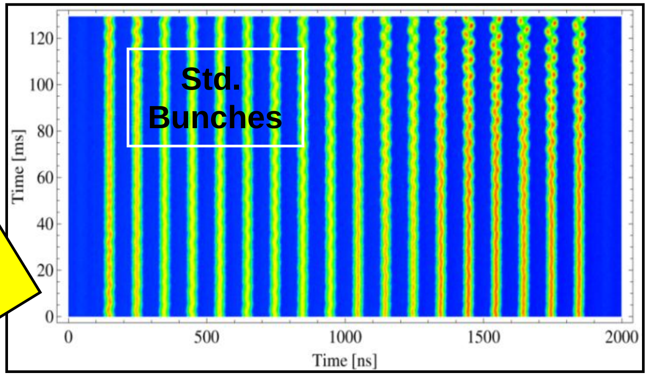
using LHC25

C. Bhat, H. Damerau, S. Hancock, E.Mahner, F.Caspers

10 MHz RF system only, 32 kV at *h* = 21

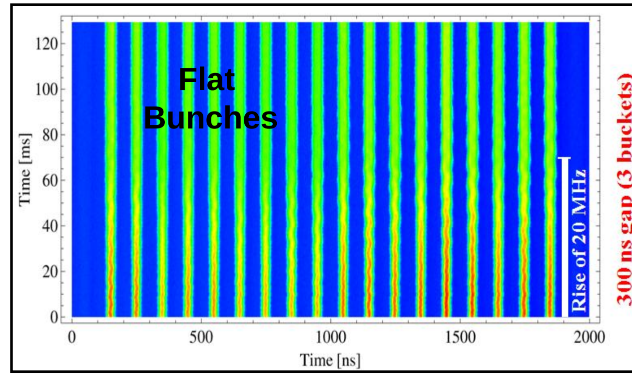
h	Vrf
21	32kV
42	0

LE(4σ)= 1.45 eVs
I=840E10/batch



Bunches in single harmonic RF

Vrf(h=21)=31kV and Vrf(h=42)=16 kV



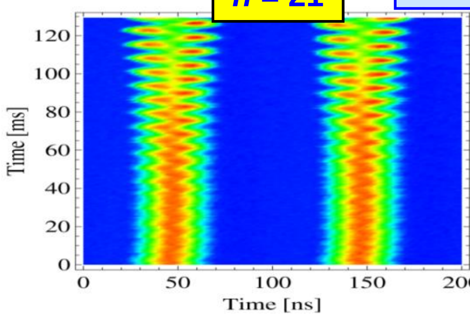
h	Vrf
21	32kV
42	16kV

$h_2/h_1=2$
$V_2/V_1=0.5$

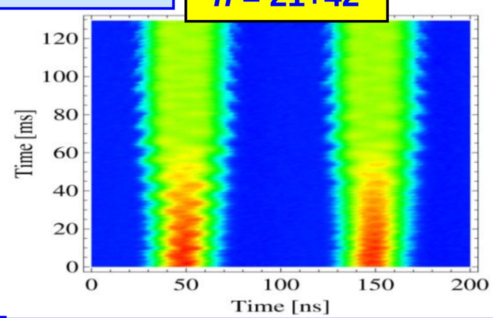
Bunches in Double harmonic RF

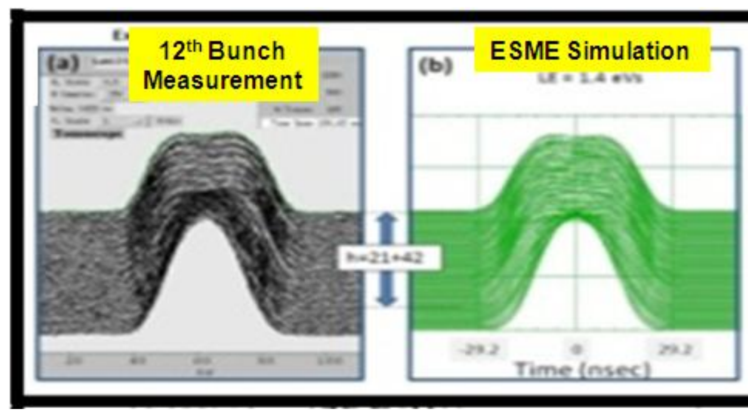
Last two bunches

h = 21



h = 21+42





Conclusions

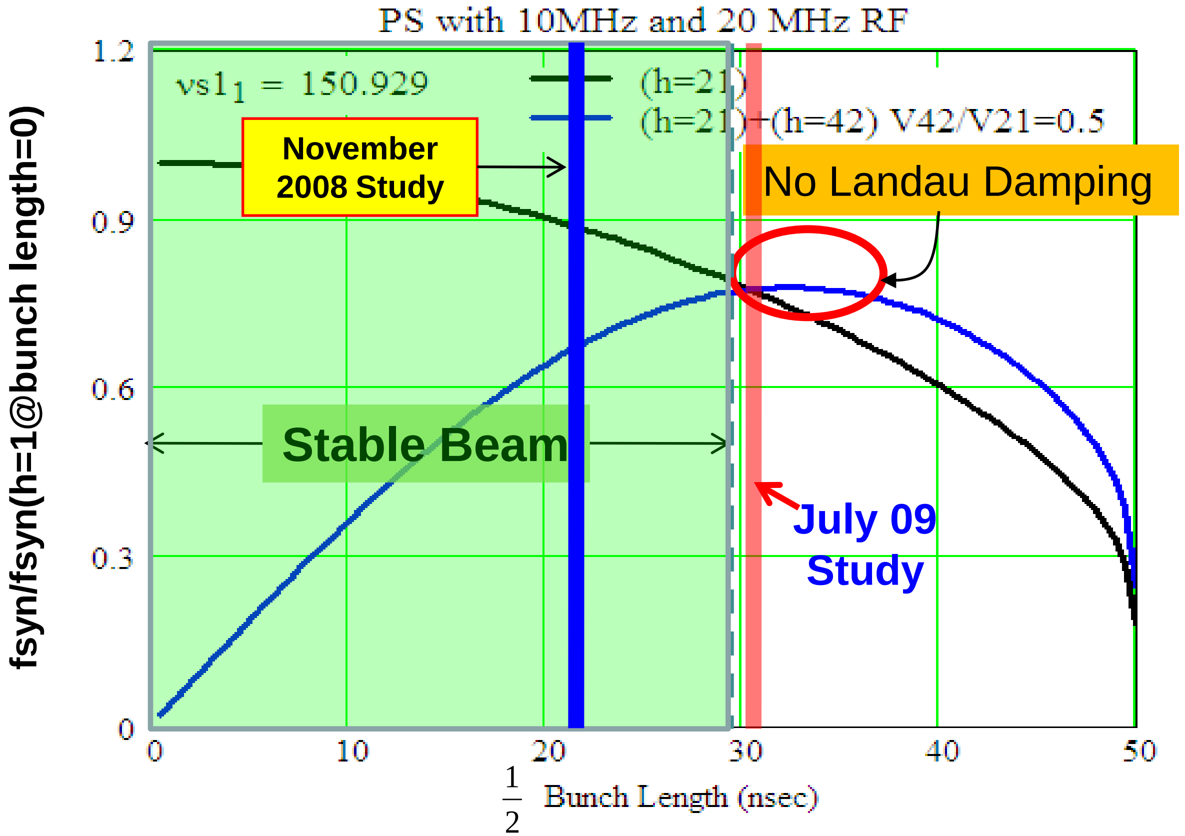
- Beam in h=21 showed coupled bunch oscillations
- Beam in DOUBLE HARMONIC rf became stable (~for 120 ms)

C. M. Bhat, et. al., PAC2009

Beam Stability Criterion in the Longitudinal Phase Space

- Large synchrotron frequency spread improves the stability.
- If $\frac{df_s}{dt} = 0$ inside the bucket, then the particles in the vicinity of this region can become unstable against collective instabilities.
  V. I. Balbekov (1987)

- As the slope of the rf wave is reduced to zero at the bunch center, the bunch becomes longer and synchrotron frequency spread is greatly increased. This increases Landau damping against coupled bunch instabilities.
  A. Hofmann & S. Myers, Proc. Of 11th Int. Conf. on HEA, ISR-Th-RF/80-26 (1980)

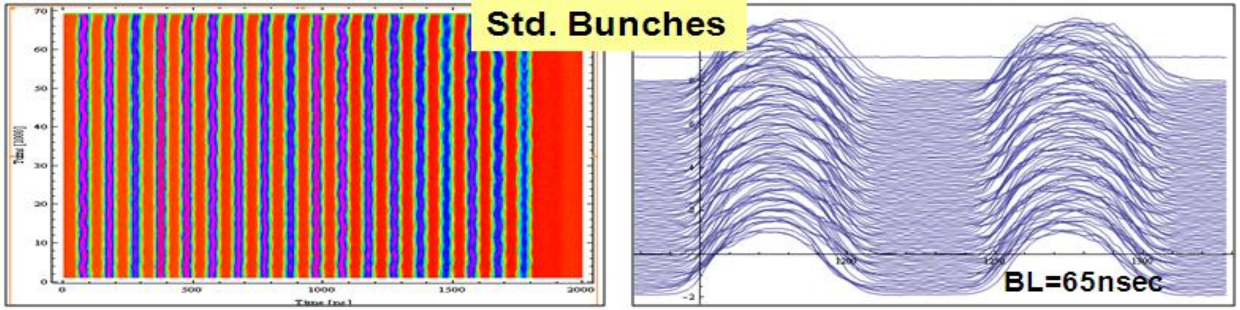


Examples from the July 09 Studies

A first look

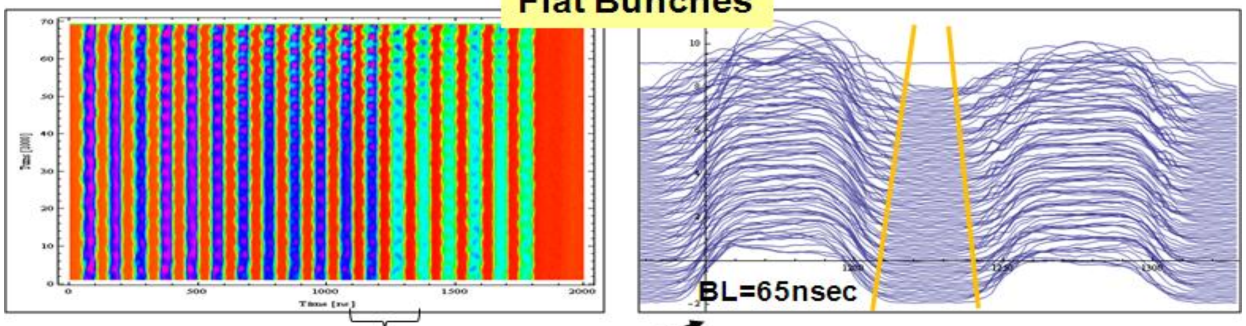
Beam (4σ) Emittance = 1.45 eVs, Batch intensity=924E10

Std. Bunches



h	Vrf
21	10kV
42	0kV

Flat Bunches



h	Vrf
21	10kV
42	5kV

Beam became unstable near the end of the cycle

Some remarks on the PS studies:

- **PS is not a storage ring and all of its RF were tuned for standard operation.**
- **Instability studies were carried out to a maximum duration of 140 ms.**

Hence, it is important to carry out Flat Bunch studies in a storage ring.

Flat bunch beam stability at the Tevatron at 150 GeV

- Tevatron is an ideal place for the flat bunch studies
  - It is world's best storage ring with many hours of beam lifetime. Well understood lattice.
  - Available RF: 53MHz. **106MHz** and **159MHz** rf systems can be added
  - Multiple bunches ← one can study a few bunches to 100s of bunches with 18 nsec bunch spacing.
  - Bunch intensity~$6x10^{10}$ protons ← bit low but, that is fine
  - Have necessary diagnostics to monitor the beam dynamics both in longitudinal as well as transverse space
    - Wall Current Monitor for measurements on longitudinal profiles
    - Flying wire and ion profile monitors
    - Add OTR ←Alex Lumpkin is proposing to add in the abort-line

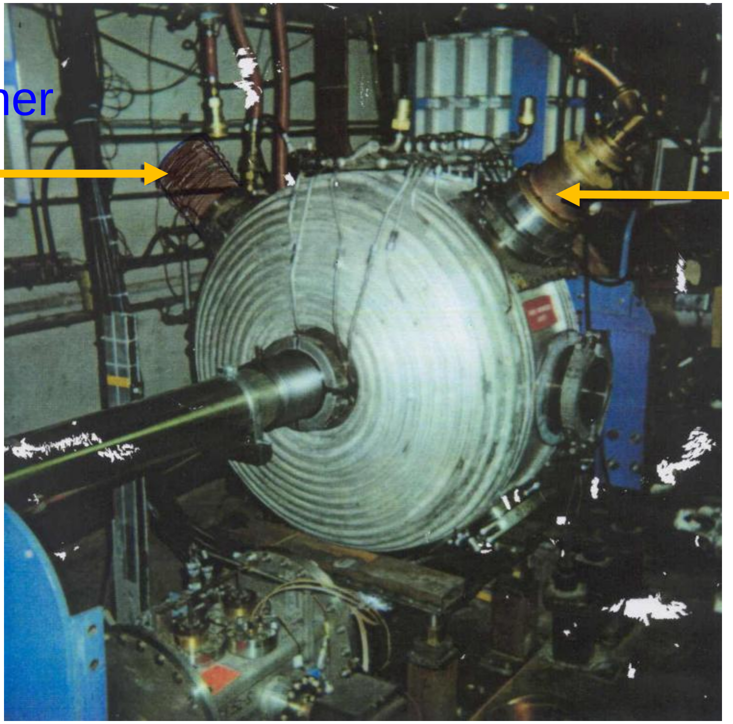
to study transverse dynamics of flat bunches

106 MHz and 159 MHz RF Cavities

106 MHz RF cavity in the MI

Currently in the MI
Used during proton and pbar coalescing
Parameters:
Frequency= 106 MHz fixed, tuned at 150 GeV
Vrf = ~9kV (maximum of 16kV)
Need some repair on water cooling

159 MHz RF cavity in the MR

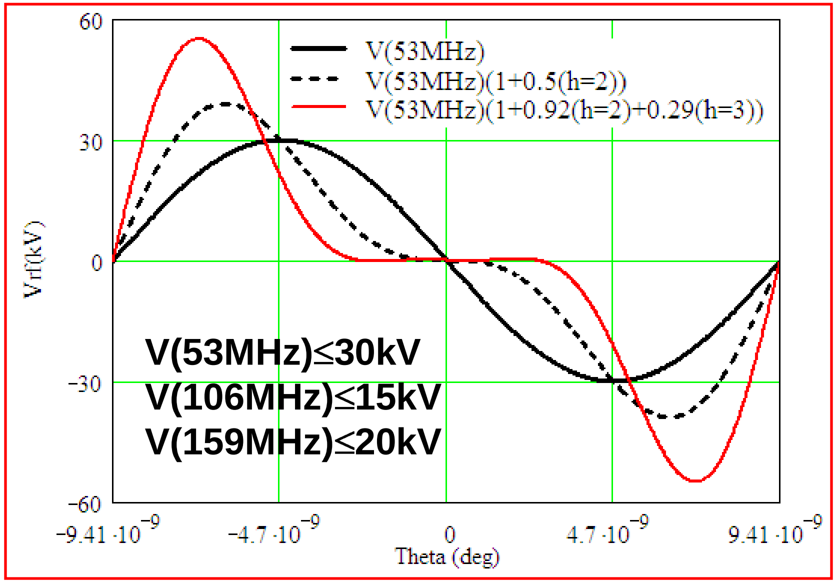


Currently in MI60 building
Used for Focus-Free Tran. crossing studies
Parameters:
Frequency= 159 MHz, tunable
Vrf = up to 250kV

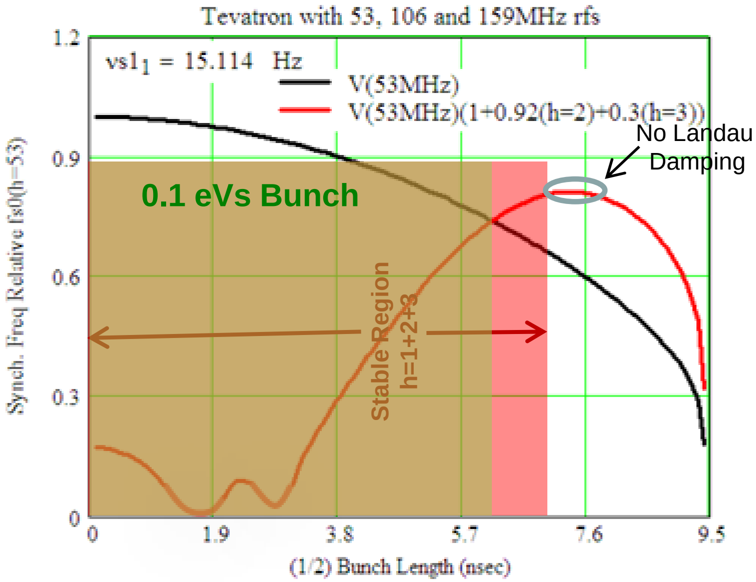
Tevatron Flat bunch Studies

Scenario-I

RF wave forms



Synchrotron Tune



Beam Energy = 150 GeV

Beam Bunch Area ≈ 0.1 eVs (Beam from the Booster+a few% growth in the MI)

Available Bucket Area = 0.7 eVs (53MHz RF wave)

= 0.57 eVs (53MHz+106MHz RF waves)

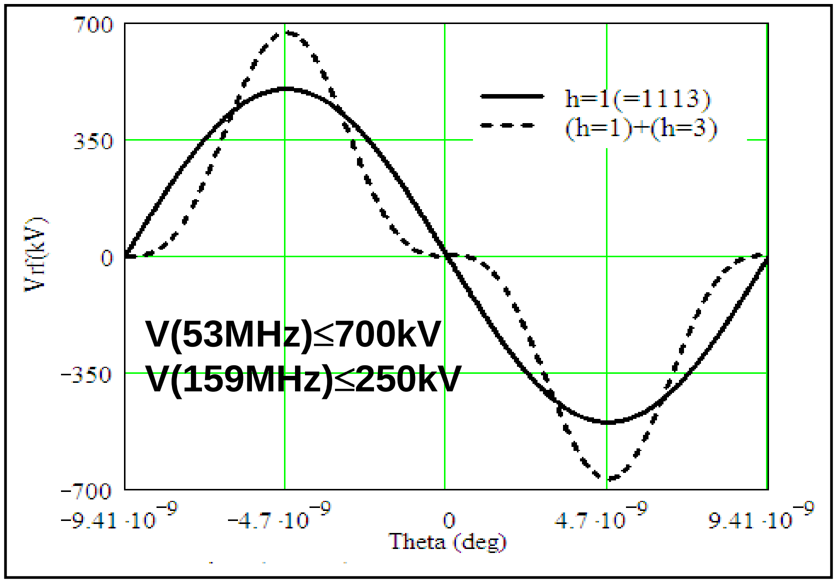
= 0.47 eVs (53MHz+106MHz+159MHz RF waves)

Limits the available Bucket Area

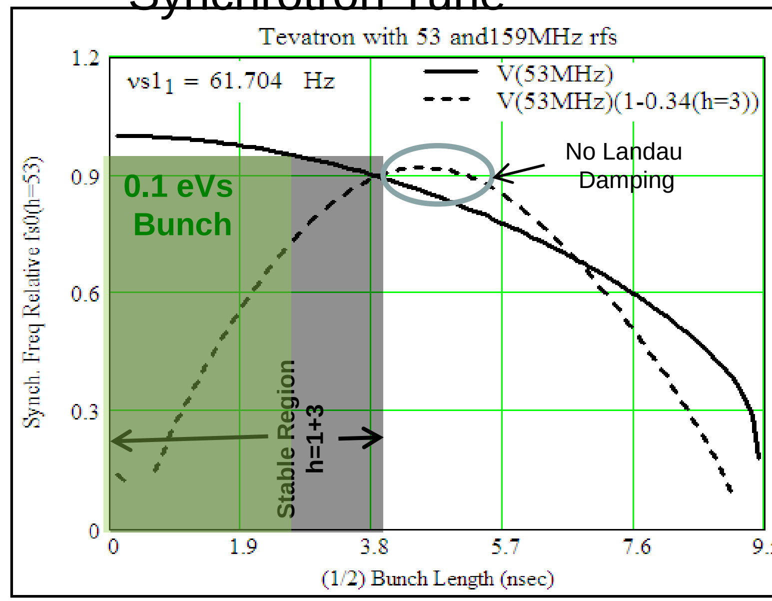
Tevatron Flat bunch Studies

Scenario-II

RF wave forms



Synchrotron Tune



Beam Energy = 150 GeV
Beam Bunch Area ≈ 0.1 eVs (Beam from the Booster+a few% growth in the MI)
Available Bucket Area = 2.98 eVs (53MHz RF wave)
= 2.66 eVs (53MHz+159MHz RF waves)

This may be more favorable and need to phase only two RF systems

As a part of LARP program we have a

Proposal

Theoretical Investigations of Flat Bunch Scenarios for the LHC Luminosity Upgrade

C. Bhat, H-J. Kim, F.-J. Ostiguy, T. Sen

Issues for Theoretical Investigations

Proposing to do theoretical investigations on the following issues --

- For creation of flat bunches, investigate the use of
  - multiple harmonic cavities (perhaps 2 to 3 harmonics) and Specify
    - Optimal RF parameters
    - Beam intensity limits
    - Reevaluate impedance budget and constraints
- If flat bunches are to be produced in one of the LHC upstream machines, explore beam instability issues for acceleration up to 7 TeV.
- Single-bunch and multi-bunch instability issues.

Issues for Theoretical Investigations (cont.)

- What are the optimal bunch and beam parameters for the LPA scheme with due consideration of the following
  - Integrated luminosity (i.e. luminosity and lifetime)
  - Emittance growth from beam-beam interactions, IBS
  - Instability growth rates
  - Beam loading compensation
  - Event pile-up: number, space and time resolution of events per bunch crossing
  - Beam losses
- Investigate possible locations and effects due the cavities in the machine lattices.
- **A hybrid scheme that would allow the FCC scheme to benefit from some of the advantages of flat bunches. This would be worth exploring.**
  - **Lower peak intensity decreases the e-cloud effect and space-charge effects**
  - **Lower momentum spread**
  - **Possibly better event resolution (spatial and time) in the detectors**

Acknowledgements

- LARP
- CERN
  - Frank Zimmermann
  - Elena Shaposhnikova
  - Steven Hancock
  - Oliver Brüning
  - Heiko Damerau
  - Thomas Bohl ← **RF issues**
  - Gianluigi Arduini ← **Inputs on beam instability in the LHC upstream accelerators.**
  - Elias Metral, Giovanni Rumolo ← **Accelerator operation issues**
  - Jim MacLachlan ← **Simulation issues**

Summary

- **We propose to carry out flat bunch studies in the Tevatron using multiple harmonic rf systems**
- **Tevatron is an ideal place for the flat bunch studies**
  - It is world's best high energy storage ring
  - Available RF for beam studies are : 53MHz, **106MHz** and **159MHz** rf systems
    - Double harmonic rf
    - Triple harmonic rf
  - Multiple bunches
  - Have necessary diagnostics to monitor both longitudinal as well as transverse dynamics
- **This effort will be the one of the most important contribution to the LHC luminosity upgrade using LPA scheme**

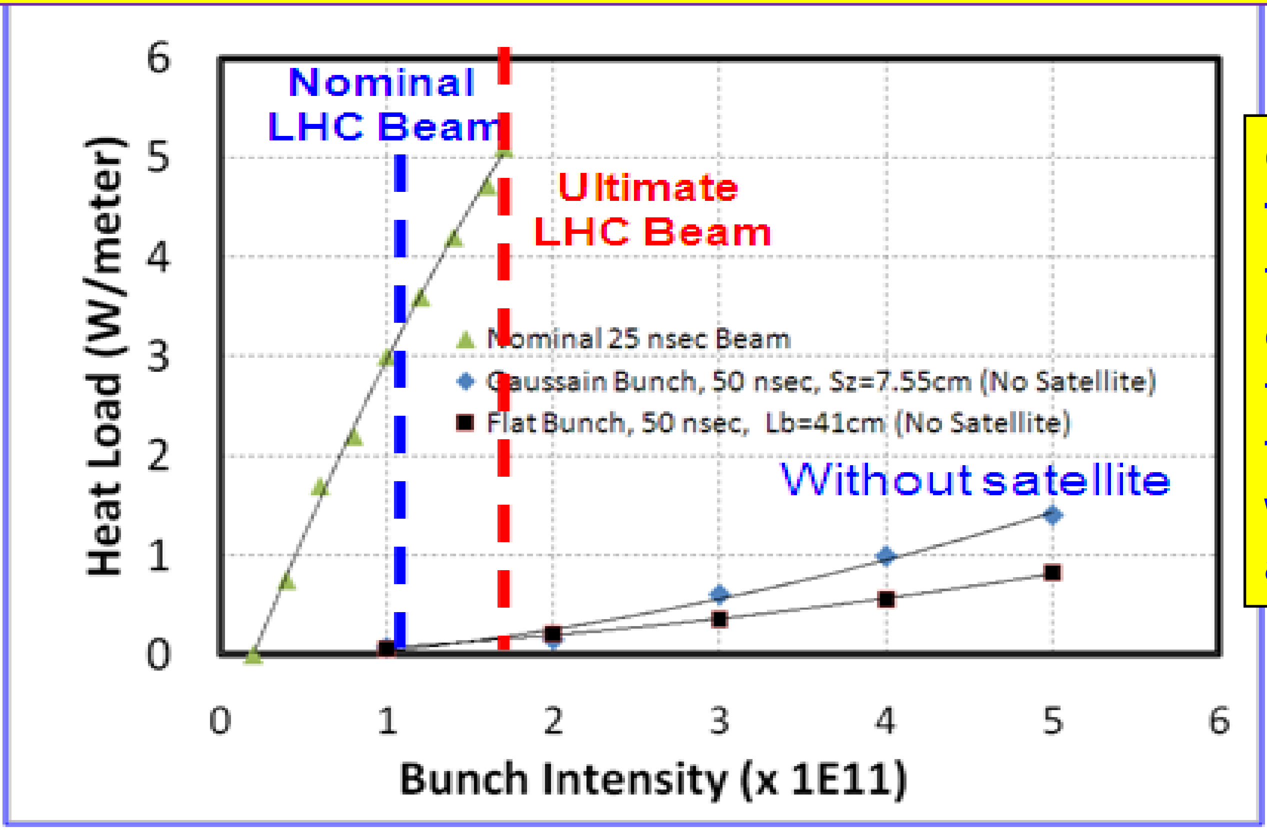
Existing Simulation Tools

- ESME
  - This is a 2D code to study longitudinal beam dynamics in (ΔE, Δt)-phase space in synchrotrons. We will use it to address
    - Flat bunch creation and acceleration with single and multiple harmonic rf systems,
    - Longitudinal single and multi-bunch instability
    - Beam loading issues.
- Beam-beam code BBSIM
  - This code will be used to study the impact of beam-beam interactions on the emittance growth. Comparisons between a longitudinal Gaussian profile and a flat profile will be made for the LPA and for the FCC schemes.
- Vlasov solver
  - This will be used to investigate long term beam stability and particle losses. Also, 1) extract spectral information and 2) help establish the optimal ratio of harmonic amplitudes and bunch length, in the presence of realistic impedances.

ECLOUD Simulations
for Gaussian and Flat bunches

Average Heat Load 2nd Batch

Frank Zimmermann (CERN) and Humberto Maury Cuna, (CINVESTAV, Mexico)



Conclusions:
The estimated heat load from the e-cloud effects on LHC cryogenics with flat bunches is about two times smaller than that with Gaussian bunches at the same bunch int..

Without satellite →